STABILITY INDEX MAP OF BUNCOMBE COUNTY, NORTH CAROLINA

FOR SHALLOW TRANSLATIONAL SLOPE MOVEMENT SUSCEPTIBILITY DURING A 5-INCH (125 MM) RECHARGE EVENT

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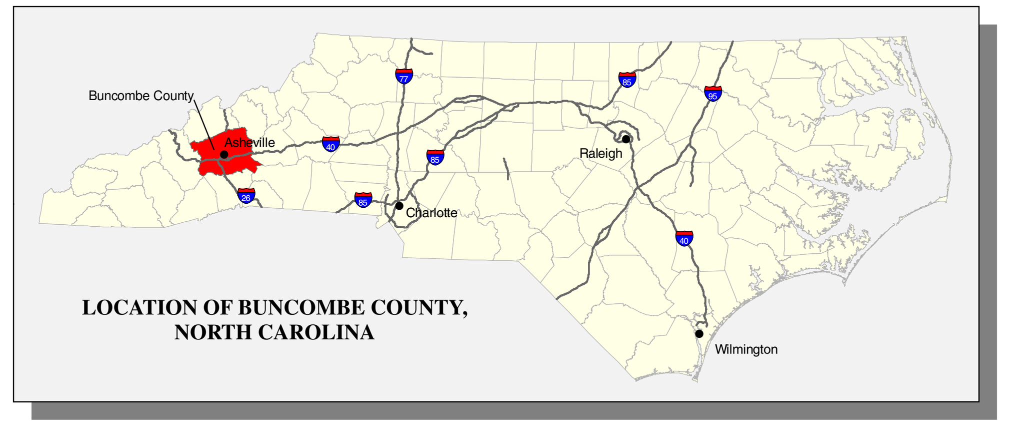
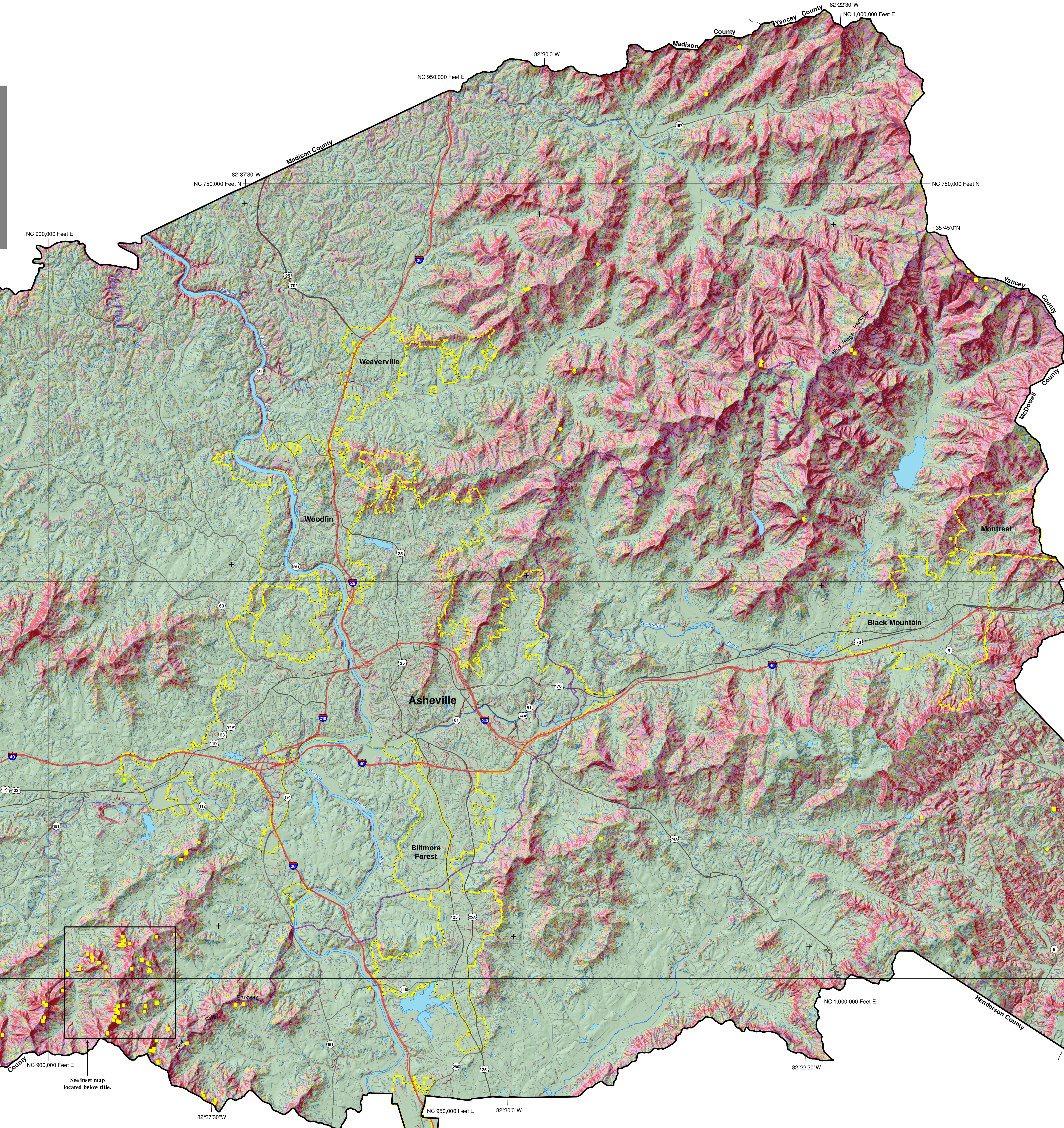
GEOLOGIC HAZARDS MAP SERIES 4
SLOPE MOVEMENT HAZARD MAPS OF BUNCOMBE COUNTY, NORTH CAROLINA
SHEET 2 OF 3, VERSION: AUGUST 24, 2009



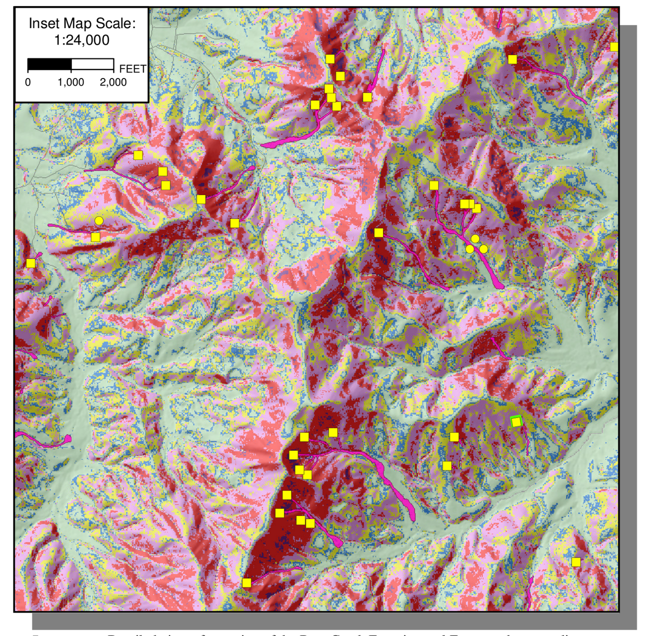
LOCATION OF BUNCOMBE COUNTY, NORTH CAROLINA



Map Information:
Datum: North American Datum of 1983
Coordinate System: North Carolina State Plane, Zone 3200
Projection: Lambert Conformal Conic
Cartography by North Carolina Geological Survey
Produced in a Geographic Information System (GIS) using ArcGIS™.

Basemap:
Hillshade derived from 20-foot resolution LiDAR (Light Detecting And Ranging) digital elevation data provided by the North Carolina Floodplain Mapping Program using an artificial sun azimuth of 315° and a sun altitude of 45°.

Based on information and data available as of August 24, 2009, concurrent with the GIS versions of the maps released to Buncombe County on this date.



Inset map. Detailed view of a portion of the Bent Creek Experimental Forest and surrounding areas showing a concentration of landslides triggered by the storm of November 3-6, 1977.

EXPLANATION

Map Color Code	Predicted Stability Zone	Relative Debris/Earth Flow/Slide Hazard Ranking[1]	Stability Index Range[2]	Factor of Safety (FS)[3]	Probability of Instability[4]	Predicted Stability With Parameter Ranges Used in Analysis	Possible Influence of Stabilizing or Destabilizing Factors[5]
	Unstable	High	0	Maximum FS <1	100%	Range cannot model stability	Stabilizing factors required for stability
	Upper Threshold of Instability		0 - 0.5	>50% of FS ≤1	>50%	Optimistic half of range required for stability	Stabilizing factors may be responsible for stability
	Lower Threshold of Instability	Moderate	0.5 - 1	≥50% of FS >1	<50%	Pessimistic half of range required for instability	Destabilizing factors are not required for instability
	Nominally Stable		1 - 1.25	Minimum FS = 1	___	Cannot model instability with most conservative parameters specified	Minor destabilizing factors could lead to instability
	Moderately Stable	Low	1.25 - 1.5	Minimum FS = 1.25	___	Cannot model instability with most conservative parameters specified	Moderate destabilizing factors are required for instability
	Stable		>1.5	Minimum FS = 1.5	___	Cannot model instability with most conservative parameters specified	Significant destabilizing factors are required for instability

Table 1. Stability class definitions for stability index map delineated using SINMAP. Modified from Pack and others (1998, Table 1).

Explanatory notes for Table 1:

[1] **Relative Debris/Earth Flow/Slide Hazard Ranking.** This column designates the relative hazard ranking for the initiation of shallow translational landslides on unmodified (i.e., natural or undisturbed) slopes.

[2] **Stability Index Range.** The stability index is a numerical representation of the relative hazard for shallow translational slope movement initiation based on the factors of safety computed at each point on a 20 foot (6 meter) grid derived from LiDAR elevation data. The stability index is a dimensionless number based on factors of safety generated by SINMAP that indicates the probability that a location is stable considering the most and least favorable parameters for stability input into the model. The breaks in the ranges of values for the stability index categories are the default values recommended by the program developers.

[3] **Factor of Safety (FS).** The factor of safety is a dimensionless number computed by SINMAP using a modified version used in Pack and others (1998) of the infinite slope equation that represents the ratio of the stabilizing forces that resist slope movement to destabilizing forces that drive slope movement (Figure 2). A FS >1 indicates a stable slope, a FS <1 indicates an unstable slope, and a FS =1 indicates the marginally stable situation where the resisting forces and driving forces are in balance.

[4] **Probability of Instability.** This column shows the likelihood that the factor of safety computed within this map unit is less than one (FS <1, i.e., unstable) given the range of parameters used in the analysis (Table 3). For example, a <50% probability of instability means that a location is more likely to be stable than unstable given the range of parameters used in the analysis.

[5] **Possible Influence of Stabilizing or Destabilizing Factors.** Stabilizing factors include increased soil strength, root strength, or improved drainage. Destabilizing factors include increased wetness or loading, or loss of root strength.

MAP FEATURES

Roads
- Interstates
- Primary Roads
- Secondary Roads
- Blue Ridge Parkway

Rivers
- Major Rivers
- Minor Rivers
- Lakes

Political Boundaries
- Municipal boundaries
- Buncombe County boundary

Slope Movement Initiation Zones
- Debris or earth blowout
- Debris or earth flow
- Debris or earth slide
- Debris or earth slide-translational
- Debris or earth slide and flow
- Green Halo Indicates a Detailed Study location

Note: Locations of slope movement initiation zones shown on this map sheet depict only shallow translational movements on unmodified slopes. These locations were used to calibrate the SINMAP model (Sheet 2). For a comprehensive listing and locations of the types of slope movements and deposits identified and/or field verified in Buncombe County, see Sheet 1 (Slope Movements and Slope Movement Deposits Map).

SLOPE MOVEMENT DEFINITIONS

Materials

debris – A soil that contains a significant proportion of coarse material; 20 to 80 percent of the particles are greater than coarse sand (0.08 inches or 2 millimeters), with the remainder finer than 0.08 inches or 2 millimeters.

earth – A soil in which approximately 80 percent or more of the particles are smaller than 0.08 inches (2 millimeters).

Mechanisms

blowout – A type of slope failure in which water and material bursts forth from the ground and then proceeds downslope as overland flow. Blowouts are possibly caused by excessive pore water pressure (Hack and Goodlett, 1960).

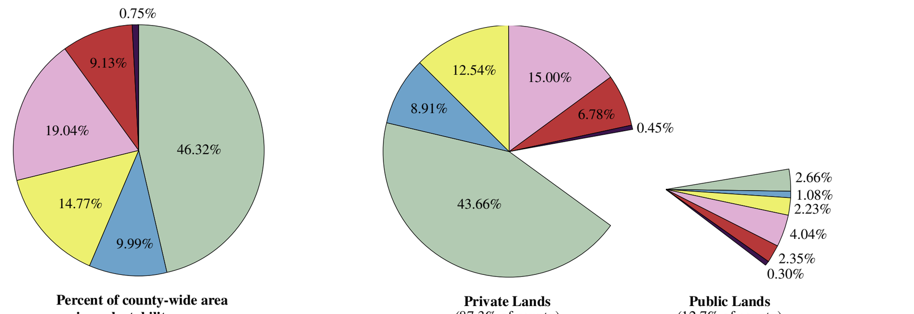
flow – A type of slope movement in which the water content in the displaced mass is sufficient for the material to liquefy and behave as a viscous fluid.

slide – Slides are slope movements initiated by outward or downward rupture of displaced material along a well-defined, typically planar or curvi-planar failure surface. Where the geometry of the failure surface is not known, the term slide is applied. Where known, the slide is classified as rotational or translational (see slide-rotational and slide-translational).

slide-translational - A slide in which the displaced material experiences little to no rotation or backward tilting as it progresses downward along a failure surface that is typically planar.

Note: Unless referenced otherwise, the above definitions are in general accordance with Cruden and Varnes (1996) and Jackson (1997) and represent slope movement types that can be modeled using SINMAP.

AREA AND LANDSLIDE STATISTICS FOR EACH STABILITY ZONE



Percent of county-wide area in each stability zone.

Private Lands (87.3% of county) **Public Lands** (12.7% of county)

Percent of county-wide area seperated into public and private lands in each stability zone.

	Stable	Moderately Stable	Nominally-Stable	Lower Threshold	Upper Threshold	Unstable	Total
Area (km^2)	791	171	252	325	156	13	1708
% of County	46%	10%	15%	19%	9%	1%	100%
Number of Landslides	0	6	10	30	62	22	130
% of Slides	0%	4%	8%	23%	48%	17%	100%
Landslides/km^2	0.0	0.0	0.0	0.1	0.4	1.7	0.1

Table 2. Statistical summary for each stability zone in Buncombe County.

OVERVIEW OF THE STABILITY INDEX MAP

Introduction

The North Carolina General Assembly authorized the North Carolina Geological Survey (NCGS) to produce landslide hazard maps for 19 western counties in response to the number of slope movements (landslides) and destruction caused by the remnants of Hurricanes Frances and Ivan in western North Carolina in September 2004. The intent of the landslide hazard mapping program is to provide the public, local government, and local and state emergency agencies with a description and location of areas where slope movements have occurred, or are likely to occur, and the general areas at risk from these slope movements. The locations of previous slope movements are important because slope movements often reoccur in the same general areas. This mapping is not intended to substitute for a detailed, onsite analysis by a qualified geologist or engineer.

The slope movement hazard map series for Buncombe County consists of three maps, Geologic Hazards Map Series 4 (GHMS-4) Sheets 1, 2, and 3 designed to be used in conjunction with each other. This map is Sheet 2. The accompanying maps are: Sheet 1, Slope Movements and Slope Movement Deposits Map of Buncombe County, North Carolina and Sheet 3, Map of Known and Potential Debris Flow Pathways in Buncombe County, North Carolina.

Stability Index Map (Geologic Hazards Map Series 4, Sheet 2)

This color-coded map delineates the predicted relative hazard rankings (high, moderate, and low) for the initiation of naturally occurring, shallow, translational slope movements (i.e., debris/earth flows, and debris/earth slides) in response to approximately 5-6 inches (125-154 mm) or more of recharge within a 24-hour period (e.g., a 5-inch recharge event is approximately equal to an addition of 5 inches of groundwater). Debris flows and similar types of landslides make up nearly 77% of the landslides recorded in Buncombe County. Throughout western North Carolina debris flows have resulted in the greatest number of landslide fatalities and damage of all reported landslide types. The three relative hazard rankings are generalized from the six predicted stability zones delineated on the map. Table 1 provides the definitions and additional information related to the predicted stability zones, relative hazard rankings, and the corresponding stability index ranges. Table 2 gives the statistical summary of slope movements for each stability zone. The Stability Index Map does not predict that shallow translational slope movements will occur, but it forecasts that if they do, where they are more likely to initiate given the assumptions and input parameters used in the analysis. Debris/earth flows and debris/earth slides typically originate where thin (usually less than 6 ft or 2 m thick) soil overlies relatively low permeability layers such as bedrock on steep slopes, typically those greater than 20 degrees (22 degrees = 40 percent). This map is intended to indicate the distribution of high and moderate hazard areas where further slope stability analysis and assessment, including field verification, is recommended prior to undertaking ground disturbing activities.

Map Production

The map was produced using SINMAP (Stability INdex MAPping) software, an ArcView™ 3.x extension developed by Pack and others (1998) for use in a geographic information system (GIS). SINMAP computes a factor of safety using the infinite slope model (Pack and others, 1998, and Hammond and others, 1992) based on the input hydrologic, soil and topographic data for each pixel on a 20 foot (6 meter) LiDAR (Light Detecting And Ranging)-derived digital elevation model grid. The factor of safety (FS) is a dimensionless number that represents the ratio of the stabilizing forces to destabilizing forces at a location. A FS<1 indicates unstable conditions, whereas a FS>1 indicates stable conditions given the assumptions and parameters input into the model. SINMAP then assigns a stability index based on the computed factors of safety. The six stability zones are assigned relative hazard rankings (high, moderate, and low) based on the calculated stability index ranges, and known slope movement occurrences. Figures 1 and 2 give basic information on parameters used in the SINMAP model to compute factors of safety and the infinite slope equation.

Model input parameters include upper and lower bounded values for recharge to the shallow groundwater system, soil transmissivity (soil permeability or hydraulic conductivity multiplied by soil thickness), and other soil properties (i.e., unit weight, thickness, effective internal friction angle, and effective cohesion). SINMAP randomly samples the bounded input parameter values using a uniform probability distribution to account for the variability and uncertainty inherent within the natural system. Soil properties were obtained from the U.S. Department of Agriculture digital soil survey of Buncombe County (United States Department of Agriculture, 2008). Mapped soil units were then combined into nine "calibration regions" having similar ranges of soil texture, hydraulic conductivity and soil depth. These data were augmented by field data collected by NCGS geologists and constrained by values from triaxial shear strength testing of soil at three detailed study sites at debris flow initiation zones, soil gradation and Atterberg limits tests of soil at 86 sites in the county, and data from the North Carolina Department of Transportation triaxial testing database. These soil classifications, descriptions, and test results, along with literature values for soil properties given in Hammond and others (1992) were used to constrain reasonable ranges of soil input parameters for the stability index modeling.

FS = factor of safety:
a = topographic catchment area
C = dimensionless cohesion = (**Cr** +**Cs**)/(**h**ρ_s**g**)
Cr = root cohesion; **Cs** = soil cohesion;
h = soil thickness; ρ_s = soil density; **g** = gravity constant
h_w = height of water;
R = recharge
r = water density (ρ_w) to soil density (ρ_s) ratio
T = soil transmissivity = soil hydraulic conductivity x **h**
Ø = soil internal angle of friction
θ = slope

h_w/h = Relative wetness = $\min\left(\frac{R\,a}{T\sin\theta},1\right)$

$$FS = \frac{C + \cos\theta\left[1 - \min\left(\frac{R\,a}{T\sin\theta},1\right) r\right]\tan\phi}{\sin\theta}$$

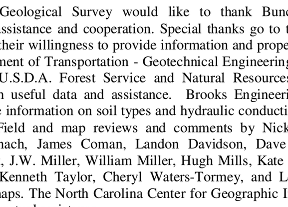


Figure 1. Schematic showing the modified version of the infinite slope equation and slope conditions used in SINMAP (adapted from Pack and others, 1998).

The stabilizing affect of vegetation is accounted for as root cohesion in the dimensionless cohesion parameter. Input values for root cohesion were constrained using the results of recent research at the U.S. Forest Service Coweeta Hydrologic Laboratory (Hales and others, 2007; Hales and others, 2008). SINMAP uses slope and topographic convergence derived from the LiDAR elevation data to model saturation in convergent hollow areas.

The 5-inch (125 mm) steady state recharge value used in the SINMAP model analysis approximates an equivalent amount of rainfall within a 24-hour period. This recharge value is used because historical evidence (Eschner and Patric, 1982; Neary and Swift, 1987; and Witt, 2005) and recent examples in North Carolina indicate that 5 inches (125 mm) of rainfall within a 24-hour period is an approximate threshold for triggering debris/earth flows and slides. Watershed studies at the U.S.D.A. Forest Service Coweeta Hydrologic Laboratory in Macon County, however, show that 3-19% of rainfall from storms is direct runoff (storm flow) rather than recharge (Hewlett and others, 1984). If this is the case, then as much as 6 inches (approx. 150 mm) of rainfall could be required to produce the 5 inches (approx. 125 mm) of recharge used in the SINMAP model analysis.

Model Calibration

The model calibration (i.e., the parameter adjustment process) was performed as recommended by the developers of SINMAP (Pack and others, 1998) using the known 130 shallow, translational slope movements shown in Table 2 (e.g., debris flows, debris slides and blowouts) that occurred on unmodified slopes (i.e., those without obvious ground-disturbing activity). Initial model runs used ranges of parameter values selected and constrained from the sources described above. Parameter values (primarily dimensionless cohesion, soil thickness, internal friction angle, and hydraulic conductivity) were then adjusted within reasonable ranges to maximize the number of slope movement locations per unit area captured in the high hazard (upper threshold and unstable) SINMAP zones.

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ACKNOWLEDGEMENTS

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CALIBRATION REGIONS AND PARAMETER VALUES USED TO GENERATE THE STABILITY INDEX MAP

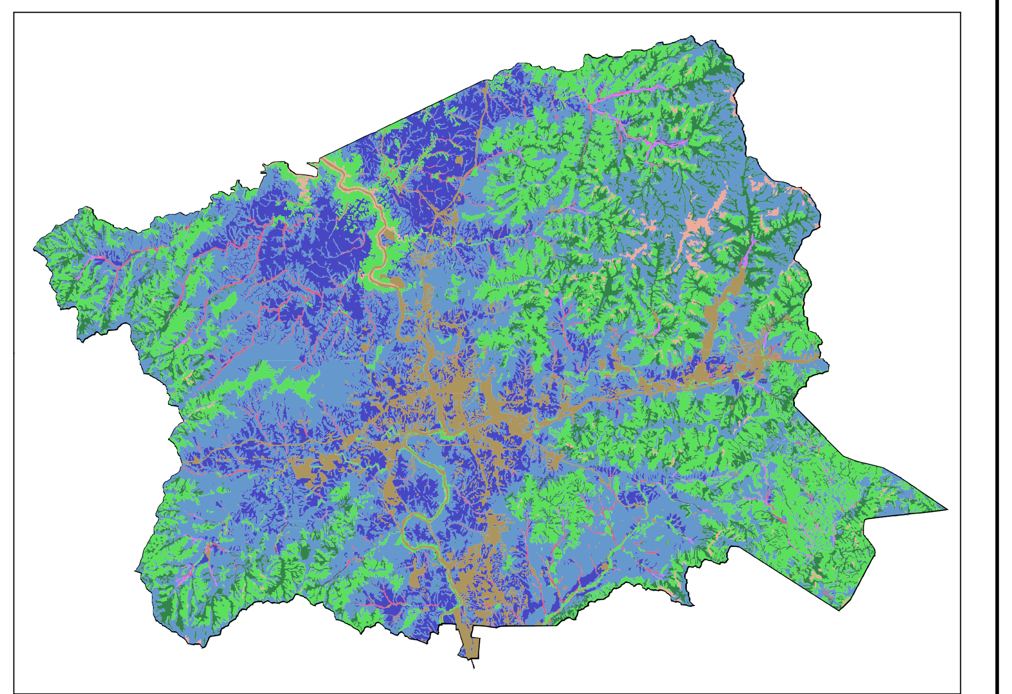

Figure 2. SINMAP calibration regions for Buncombe County derived from the Soil Survey Geographic database for Buncombe County (United States Department of Agriculture, 2008).

Region[1]	Calibration Unit[2]	T/R (m) Low[3]	T/R (m) High[3]	Dimensionless Cohesion Low[4]	Dimensionless Cohesion High[4]	Friction Angle (degrees) Low[5]	Friction Angle (degrees) High[5]
1	BeA, CuB, DAM, ExC, ExD, Pg, Pt, UcB, Ud, UfB, UhE, UrB, UrC, Ux, W	0.9	229.3	0.17	0.09	23	42
2	BkB2, BkC2, BkD2, BnB, BnC, CkB2, CkC2, CkD2, CkE2, CsB, CsC, CsD, CuC, CuD, HpA, KsB, KsC, UnB, UnC, UnD, ZcB, ZcC, ZoD	2.8	115.4	0.10	0.35	23	38
3	BpF, BwD, BxE, BxF, ChD, ChE, ChF, DrB, EvD2, EvE2, EvF2, EwC, EwD, EwE, EwF, ExE, FaC2, FaD2, FaE2, FnB, FnC, FnD, JbB, JbC, JbD, JbE, OwC, OwD, OwE, OwF, PwC, PwD, PwE, PxF, StB, TaB, TaC, TaD, TkC, TkD, TmB, TmC, TmD, TsA, TtE, TuD, TwB, TwC, UkD, UkE, UkF, WoE, WpF, WrC, WrD, WrE, WsF, WtB, WtC	0.9	106.1	0.28	0.33	23	40
4	FrA	1.1	197.8	0.34	0.65	23	45
5	AcD, ArE, ArF, EdC, EdD, EdE, EdF, IoA, MvD, MvE, MvF, MwD, MwE, MwF, RsA, SoD, SoE, SoF, SyD, SzF, WaC2, WaD2, WaE2, WnF	1.1	138.9	0.33	0.27	24	42
6	NkA, RdA,	19.6	197.8	0.25	0.53	24	45
7	BaD, BaE, CaE, CdF, HcE, NtD, NtE, SyE, TnE, ToC, TpD, TpE	3.8	122.1	0.25	0.40	24	45
8	DeA	3.7	197.8	0.34	0.53	24	45
9	CxF, RkF, CxE, RoF	0.3	42.3	0.46	0.15	33	45

Table 3. Calibration regions and parameters used to generate the Stability Index Map.

Explanatory notes for Table 3:

[1] **Region.** A numbered area used in the SINMAP modeling process with similar soil, geologic, and hydrologic properties derived from the Soil Survey Geographic database for Buncombe County (United States Department of Agriculture, 2008). Each region is made up of map units grouped according to similar soil properties. Individual upper and lower bounded value estimates for T/R (ratio of soil transmissivity to recharge), dimensionless cohesion, and soil friction angle were derived for each region.

[2] **Calibration Unit.** Abbreviations for soil map units from the Soil Survey Geographic database for Buncombe County (United States Department of Agriculture, 2008) grouped into calibration regions.

[3] **T/R (m) Low/High.** The upper and lower bounding values for the ratio of soil transmissivity (T) to the rate of recharge (R). Transmissivity was calculated by multiplying the hydraulic conductivity (permeability) of the soil by the thickness of the soil. Values for soil hydraulic conductivity were derived primarily from the Soil Survey Geographic database for Buncombe County (United States Department of Agriculture, 2008) and checked against values at three detailed study sites, data from elsewhere in the county, and those reported in the literature. Values for soil thickness were derived primarily from field data collected by the N.C. Geological Survey. The recharge rate was modeled as 5 inches (125 mm) per day, the minimum threshold rate for debris flows to initiate in the Southern Appalachians (Eschner and Patric, 1982). The value for T/R represents length of hillslope, in meters, required to develop soil saturation during the 24-hour recharge period considered.

[4] **Dimensionless Cohesion Low/High.** The upper and lower bounding values for dimensionless cohesion. These calculated estimates were derived using the ratio of the combined values for effective soil and root cohesion relative to the soil density and thickness, as shown in Pack and others (1998).

[5] **Friction Angle (degrees) Low/High.** The upper and lower bounding values for the effective internal soil friction angle. Internal friction is the friction between individual grains within a mass of material.